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Flexible integrated gasification co-generation facilities A technical and energy analysis

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Abstract

The aim of this study was to identify and analyse the technical and energy impacts of feedstock and product flexibility on integrated gasification co-generation facilities (IGCF) using current commercial ready technologies. The evaluation was twofold: 1) to identifying bottlenecks and possible de-bottleneck solutions and 2) to analyse flexibility effects on overall plant performance. Results indicate that flexibility is technically possible. Overall plant performance shows a minor drop in efficiency when switching from coal to Eucalyptus. When using torrefied biomass this drop almost completely disappears.

Keywords: Gasification; flexibility; techno-economic; methanol;

1. Introduction

In 2007 global oil consumption was above 160 EJ, much of which was used in the transport sector. The remaining oil is mainly used for heat, chemical and electricity production.[1] Usage is expected to increase as developing countries are building up their economies. Extracting and refining the required amount of oil already gives problems today due to lack of extraction/refining capacity and the geopolitical concentration of oil reserves. It is expected that these problems will increase in the future. As oil-derived end products are vital for most economies, alternatives must be found. One of those alternatives is gasification of biomass or coal to produce electricity, heat, chemicals and fuels.

An integrated gasification co-generation facility (IGCF) converts coal or biomass into syngas, a gas with a high hydrogen (H_2) and carbon monoxide (CO) content. Syngas is combusted for electricity production or converted into chemicals and fuels using catalysts. Compared to conventional power plants, IGCF has several advantages. 1) They produce low amounts of waste. The major by-products sulphur and slag are reusable. 2) They have a high efficiency (49%). A state-of-the-art pulverized coal (PC) power plant is slightly less efficient (45%). This difference increases

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with several percent points when carbon dioxide (CO_2) capture is applied (43% for IGCF versus 35% for PC). 3) They are, to a certain extend, feedstock and production flexible.

However, IGCF also has some drawbacks. The main drawbacks are the high investment costs, complexity of the process and uncertainty about legislation, e.g. CO_2 emission limits, and future commodity prices. Making IGCF flexible for both feedstocks and end products would allow the facility to follow market behaviour. This can increase profits as, compared to a static IGCF, cheaper feedstocks could be used to produce more expensive end products.

Although research on IGCF is extensive and growing, most of theses studies assume that both feedstock and production remain identical. This has created a knowledge gap concerning whether flexible IGCF is possible and how plant performance will react. This study seeks to answer these questions. The goal of this article is twofold:

- First, to identify where, which bottlenecks occur when switching from feedstock or production and how these bottlenecks can be resolved. The effect of flexibility on the CO_2 capture ratio and CO_2 emission ratio is also investigated. The CO_2 capture ratio is the fraction of the carbon from the feedstock that is used for CO_2 transport and storage. It does not include the amount of carbon stored in the produced fuels and chemicals. The CO_2 emission ratio is the carbon fraction that is emitted with the flue gasses and other waste streams.
- Second, to analyse the changes in overall efficiency when changing feedstock or production.

This paper has the following structure: methodology is described in section 2, results are given in section 3 and discussion and conclusion are given in section 4.

2. Methodology

A flexible IGCF is a complex installation with dozens of processes. In order to accurately calculate conversion rates and mass- and energy streams, a computer model in AspenPlus of an IGCF has been made. For each process, its conditions were entered into the model and the processes were linked in the appropriate order. This enabled the model to calculate the mass- and energy balances of the entire IGCF. It also allowed the division of the model into several distinct blocks: ***pre-treatment***, air separation unit (***ASU***), ***gasifier***, ***syngas cleaning and optimisation***, acid gas removal (***AGR***), syngas conversion (***power***, ***FT-***, ***methanol*** and ***urea*** production) and ***steam section***. For each block several alternatives were evaluated. The selected alternatives are described in section 2.1. Using the model, several case studies were used to examine the technical effects of feedstock and production flexibility. The case studies are described in section 2.2.

2.1. Flexible integrated gasification co-generation facility model

The model is divided into the distinct blocks described above. These blocks are further described below. The description generally follows the path from feedstock to product. The model is displayed in Figure 1. ***Pre-treatment***, ***ASU*** and ***gasifier*** sections are the centre left block. ***Syngas cleaning and optimising*** is the centre block. ***AGR*** is the lower centre block. The four conversion sections are the ***power*** (upper left), **methanol** (upper right), ***FT*** (lower right) and ***urea*** (lower left) sections. The ***steam section*** is inside the power section. Note that the pre-treatment and steam sections are inside a hierarchy block, which summarises the different processes into a single block.

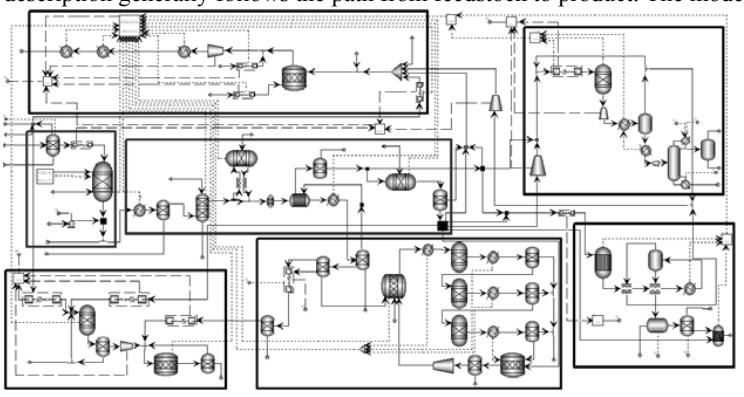

Figure 1 Flowsheet of an IGCF

The ***pre-treatment*** section consists of a dryer, cutter and pressuring system. There is a separate train for coal and for biomass. Final moisture content will be 7.5 mass% for coal, 5 mass% for torrefied Beech pellets and 10 mass% for Eucalyptus pellets. The necessary heat is supplied by the flue gas exhaust of the gas turbine. Feedstock particle size is also different for coal and biomass. Coal needs a maximum particle size of 0.1 mm to ensure high carbon conversion rates. The higher reactivity of biomass means that particle size can be up to 1.0 mm. Although biomass is more difficult to cut than coal, the bigger particle size results in an electric consumption of 0.015 kWe/kWth[2].[2] The difference in particle size also affects the pressuring system. Coal needs a lock-hopper system with pneumatic feed, while biomass can use the more efficient hydraulic piston with screw feeding. Both systems use CO_2 as pressurising agent and raise the pressure to 40 bar.

- The ***ASU*** section consists of a cryogenic ASU and an oxygen compressor. It produces 95 mol% pure oxygen at 48 bar and pure nitrogen at slightly above atmospheric pressure. A non-integrated ASU is selected as a change in product results in large turbine load variations, while ASU load remains constant. Electric consumption for the separation is 0.3 kWh/kg oxygen.
- The ***gasifier*** section consists of the gasifier and quench. For this study a dry fed, pressurised, oxygen-blown slagging entrained flow (EF) Shell gasifier is chosen for the following reasons:
  - A dry feeding system is considered more feedstock flexible. It also allows for higher efficiencies as less water is evaporated. Especially for low energy density feedstocks, e.g. biomass, the cold gas efficiency, the fraction of chemical energy in the syngas, can drop from 70% for dry feeding to 45% for slurry feeding.
  - The high pressure will allow smaller and more efficient downstream equipment, drastically reducing investment costs. It also reduces compression duty prior to the syngas conversion reactors.
  - An EF gasifier is chosen as the high temperatures (>1500ºC) inside the gasifier result in a syngas with a high H_2 and CO content and a low methane and tar content. As only the power section can handle methane and tar, the use of lower temperatures require an additional tar cracker and methane reformer if chemicals or fuels are produced. The high temperatures also improve carbon conversion.
  - Oxygen instead of air is used as oxidising agent as air will dilute the syngas with nitrogen. The nitrogen concentration in the syngas decreases from over 50 mol% for air to less than 1 mol% for oxygen.
  - The slagging mode is a consequence of the high temperatures. In this mode, the ash in the feedstock melts and sticks to the wall. There it flows downwards and is quenched in a water bed resulting in a solid glass-like slag. The molten ash is used as a protective layer. If this layer becomes too thin, the reactor wall can be damaged by the harsh conditions inside the gasifier.
  - The Shell EF gasifier was selected as this type is considered moderately fuel-flexible. Also, this type of gasifier gas been used for extensive biomass co-feeding tests at Buggenum.

  The model assumes a heat loss of 4% of the feedstock thermal energy and a 99.5% carbon conversion. The composition of the syngas is at thermodynamic equilibrium. This is justified as the high temperature ensures fast reaction rates. Steam is added to maintain a methane content below 500 ppm. After the gasifier, the syngas is quenched. This is to prevent fouling of downstream equipment. A water quench is selected as this gives synergies with the downstream sour water-gas shift. The quench uses pressurised water and lowers the temperature of the syngas to 850ºC. This temperature is slightly lower than the 900ºC used by coal operated gasifiers as biomass causes increased fouling. Experiments demonstrated that the 50ºC drop adequately prevents fouling. Note that the amount of syngas created in the gasifier is kept constant regardless of the used feedstock.
- The ***syngas cleaning and optimising*** section consists of a filter, wet scrubber, sour shift, COS hydrolyser, AGR, guard bed, sweet shift and H_2 PSA. The high carbon conversion makes a cyclone unnecessary. Heat exchangers and economisers are used to maximise heat utilisation. The syngas leaving the quench is cooled to 230ºC. The gas is cleaned using a candle filter for the large particles and a wet scrubber for the smaller particles and halides. Due to the high pressure, the syngas can exit at 175ºC. The next step is the sour water-gas shift (WGS). Only a part of the syngas is directed through the sour WGS reactor. This fraction is controlled to ensure a H_2:CO ratio after the AGR of 2.3. This is the optimal ratio for the FT-synthesis, which has the largest CO fraction. Steam is added to the sour WGS as the molar ratio H_2O:CO must be greater than 1.65 to prevent carbon deposition. After the shift, the syngas is hydrolysed in the COS hydrolyser. Here carbonyl sulphide (COS) and hydrogen cyanide (HCN)

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[2] All energy values are in higher heating value, unless mentioned otherwise.

are converted to hydrogen sulphide (H_2S) and ammonia (NH_3). Now the syngas is ready for the AGR. After the AGR a guard bed ensures that no sulphur is left in the syngas. If a greater H_2:CO ratio is desired, (part of) the syngas is directed to the sweet WGS followed by a H_2 PSA. The PSA extracts 90% of the H_2 in a pure H_2 stream. The waste stream of the PSA is directed to the gas turbine. The syngas is directed to the different conversion processes and pure H_2 is added if needed.

- The ***AGR*** comprises of a Rectisol unit to separately extract CO_2 and sulphuric compounds from the syngas, a CO_2 compressor to compress the extracted CO_2 and a sulphur processing unit to convert the sulphuric compounds to elemental sulphur. The sulphur processing unit is a Claus/SCOT combination. Total sulphur recovery of 99.7+%. The CO_2 compressor delivers at 110 bar. The pressurised CO_2 can be used for urea production or CO_2 transport and storage.

There are four conversion sections. Based on expert interviews it is assumed that each conversion section can only operate between 30% part load and full load. The 30% rule limits the production of off-spec products, i.e. products that do not meet the required specifications, and reduces start-up and shutdown problems.

- The ***power*** section generates electricity. Therefore syngas is combusted in a gas turbine. The heating value of the syngas entering the gas turbine is kept at 4.3 MJ_{LHV}/Nm^3. The heating value of the syngas is lowered by adding nitrogen from the ASU or steam from the steam section. Air is added at a 10% stoichiometric excess. After combustion, the flue gas is cooled to 1415ºC using air. The flue gas is then expanded, generating electricity. A series of heat exchangers cools the flue gas to 150ºC. The flue gas is then vented into the atmosphere.
- The ***FT-***section uses Co-catalysts to convert syngas to FT-fuels. A once-through concept with a 90% CO conversion rate is used in the model. The FT reactor operates at 230ºC and 59 bar. The optimal H_2:CO ratio is 2.3. Unconverted syngas and C_1-C_4 hydrocarbons are directed to the gas turbine. Heavier hydrocarbons are distilled and cracked. The required H_2 for the cracker is supplied by the H_2 PSA. The final products are FT-gasoline and FT-diesel.
- The ***methanol*** section uses a once-through slurry reactor concept with a 40% conversion rate. The methanol reactor operates at 250ºC and 69 bar. Optimal H_2:CO ratio is 3.7. Unconverted syngas is directed to the gas turbine. The methanol is purified using several flashes and a distiller. The produced methanol is 99.9+% pure.
- The ***urea*** section uses a 90% recycle concept for the ammonia reactor and a full recycle for the urea reactor. The ammonia reactor operates at thermodynamic equilibrium, while the urea reactor has a 60% CO_2 conversion rate. The ammonia reactor operates at 300ºC at 100 bar, while the urea reactor operates at 180ºC and 138 bar. The H_2:N_2 ratio for the ammonia reactor is 3. The CO_2:ammonia ratio for the urea reactor is 2. The offgas from the ammonia reactor is send to the gas turbine. The produced urea is mixed with an equimolar amount of water.

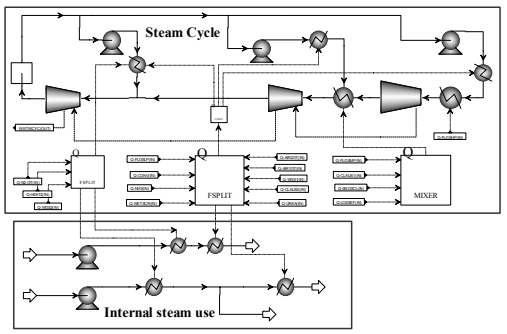

Figure 2 Steam Section

- The **steam** section is divided into four parts which are based on the maximum reachable temperature: 150ºC, 200ºC and 550ºC (2x). The low temperature parts are used for pre-heating, internal steam demand and low steam pressure cycle. The third and fourth parts are used for intermediate and high pressure steam cycle. The steam cycle uses pressures at 125, 42, 12.5 and 0.025 bar.

2.2. Case studies

Four different case studies were analysed in this article. These are: feedstock to FT-fuels, to methanol, to urea, and to electricity. When chemicals are produced, electricity is produced as by-product. During each case study the following feedstocks were used: Illinois #6 coal, pelletised torrefied Beech (TOPS) and Eucalyptus pellets. Their properties are displayed in Table 1. All case studies use the same general plant configuration as described above, although certain process may be shut down. Each case study starts with 1000 MWth input of coal. The coal is

substituted by either Eucalyptus or TOPS. This is done in steps of 20 mass%. During the substitution the generated gas volume of the gasifier is kept constant.

Table 1 Feedstock parameters [3]

	Unit	Eucalyptus	TOPS	Illinois #6
Energy content	MJ/kg wet	17.42	20.38	27.14
Moisture	mass% wet	10.0	5.0	11.12
Carbon	mass% dry	49.52	53.89	71.72
Hydrogen	mass% dry	5.77	5.60	5.06
Oxygen	mass% dry	43.98	38.92	7.75
Nitrogen	mass% dry	0.14	0.22	1.41
Sulphur	mass% dry	0.03	0.02	2.82
Chloride	mass% dry	0.06	0.01	0.33
Ash	mass% dry	0.50	1.34	10.91

To examine the effects of feedstock flexibility, three different efficiencies have been calculated using the following equations. Note that equation (1) and (2) ignore thermal energy.

(1) $$\text{Cold gas efficiency} = \frac{\text{MWth}_{\text{syngas after gasifier}}}{\text{MWth}_{\text{feedstock}}} * 100\%$$

(2) $$\text{Clean syngas efficiency} = \frac{\text{MWth}_{\text{H2+CO after gas cleaning}}}{\text{MWth}_{\text{feedstock}} + \text{MWe}_{\text{consumption}}/\alpha} * 100\%$$

(α is electric efficiency, which is assumed to be 40%)

(3) $$\text{Plant efficiency} = \frac{\Sigma\ \text{MWth products} + \text{MWe}_{\text{net}}}{\Sigma\ \text{MWth feedstock}} * 100\%$$

3. Results

This section is divided into three parts: 1) the effects of feedstock substitution on gasification and gas cleaning. 2) The extend to which product flexibility is possible and the effect of feedstock substitution on the flexibility. 3) The effect of feedstock substitution on overall plant performance.

- Feedstock flexibility will affect the feeding, gasifier and gas cleaning sections. Biomass is much more fibrous than coal, requiring a hammer mill instead of crusher. Biomass can use a more efficient feeding system. It is therefore advised to use a dedicated pre-treatment train for Eucalyptus and TOPS and a different train for coal.
  - The gasifier has several points of interest. The main effects are summarised in Table 2. 1) Thermal input is reduced when switching from coal to coal or TOPS (Figure 3) due to the lower energy density of biomass. As the generated gas volume in the gasifier is kept constant, the lower energy input can not be compensated by injecting more biomass. Thermal input reduction deviates from a straight line in favour of higher thermal input. 2) Slag production drops from 13 t/h for coal to 0.7-2 t/h for biomass. This as the low ash content in biomass is only partly compensated by the higher feedstock consumption rate. 3) Ash melting temperature increases. The ash composition is biomass is different from that of coal. The result is a higher ash melting point. A slagging agent can be added to lower the ash melting point. 4) Total oxygen consumption drops. Biomass is already partly oxidised, resulting in a lower specific oxygen consumption. 5) Gasifier efficiency drops with biomass. The lower energy density of biomass results in a higher combustion fraction compared to coal. 6) This higher degree of combustion also effects syngas composition.

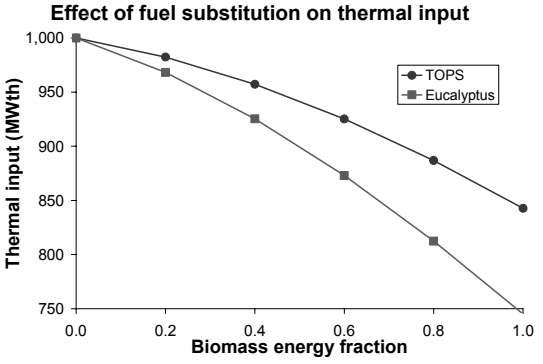

Figure 3 Effect biomass fraction on thermal input

Table 2 General parameters gasifier

	Unit	Wood	TOPS	Coal
Feedstock input	MWth fuel	745	843	1,000
	t dry fuel/hr	140	141	118
Oxygen consumption	kg O_2/kg dry fuel	0.61	0.61	0.89
	kg O_2/GJth fuel	32	28	29
Cold gas efficiency	%	70	75	81
Syngas Composition				
H_2O	(mol% wet)	25	16	2
H_2	(mol% dry)	27	29	30
CO	(mol% dry)	54	60	65
CO_2	(mol% dry)	17	10	1
Other	(mol% dry)	2	2	3

o After the syngas cleaning section, including the sour water-gas shift, syngas composition is identical regardless of used feedstock (Table 3). However, total flow is reduced from 64 Nm^3/s for coal to 51 Nm^3/s for TOPS and 42 Nm^3/s for Eucalyptus. The amount of CO_2 captured remains almost constant regardless of biomass substitution. As total carbon inputs drop when using more biomass, CO_2 capture ratio increases from 27% for coal to 31% for TOPS and 34% for Eucalyptus. The sulphur flow in the sulphur processing units drops from 3.3 t/hr for coal to under 0.05 t/h for biomass.

Table 3 Cleaned syngas specifications

	Unit	Wood	TOPS	Coal
Energy density	MJ/Nm^3	12	12	12
Gas Volume	Nm^3/s	42	51	64
Cleaned gas eff.	%	70	75	79
Syngas Composition				
H_2O	(mol% wet)	1	1	0
H_2	(mol% dry)	68	68	68
CO	(mol% dry)	29	30	30
CO_2	(mol% dry)	0	0	0
Other	(mol% dry)	2	2	2

- End product flexibility is mainly restricted by the minimum 30% load restriction and the 4.3 MJ_{LHV}/Nm^3 heating value of the syngas entering the gas turbine. Within these limitations the steam section can fulfil total internal demand and still supply to the steam turbines. The main problem is the 30% load limitation. Especially when raw biomass is used, end product flexibility is severely reduced as syngas volume after cleaning is already reduced by 35%. Where coal-derived syngas has a product flexibility between 30% and 100%, Eucalyptus-derived syngas has a flexibility of only between 45% and 100%, i.e. when using chemical production utilising maximum coal-derived syngas, load can be reduced to 30%. But, when switching to Eucalyptus, load can only be reduced to 45%.

o The energy density limitation only gives problems when producing urea. Both during FT- and methanol production the offgas of these processes is big enough to achieve a high energy density in the gas turbine. The offgas even needs dilution. The urea offgas stream is low and saturated with N_2. This stream and the large H_2-poor stream leaving the H_2-PSA result in a too low energy density. To increase the energy density either co-natural gas can be firing or 10% of the cleaned syngas is directly to the gas turbine, limiting urea flexibility for coal-derived syngas to 27-90%.

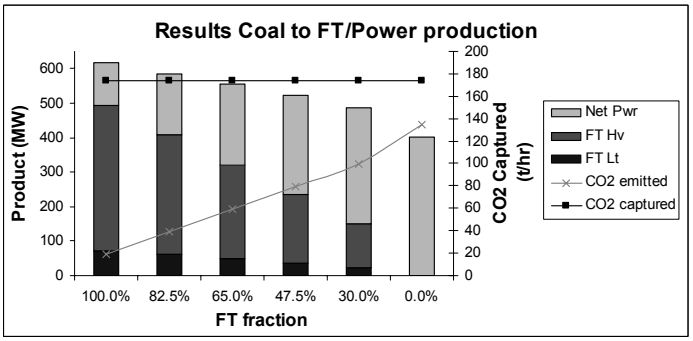

Figure 4 Effect substituting FT-production for power production

o When switching from FT production to electricity production, total efficiency drops as FT-production is more efficient than power production. Although CO_2 capture rates remain constant, CO_2 emissions increase as less CO_2 is stored in the FT-fuels. Relation between production load and output is displayed in Figure 4.

- Overall plant output drops when coal is substituted by biomass (Figure 5). This drop is larger for Eucalyptus than for TOPS. Although on first sight, it appears that using Eucalyptus results in a large efficiency reduction, note that the thermal input for Eucalyptus is also reduced, as described above. This also means that, although the CO_2 amount captured remains constant, CO_2 capture ratio is increasing for biomass.

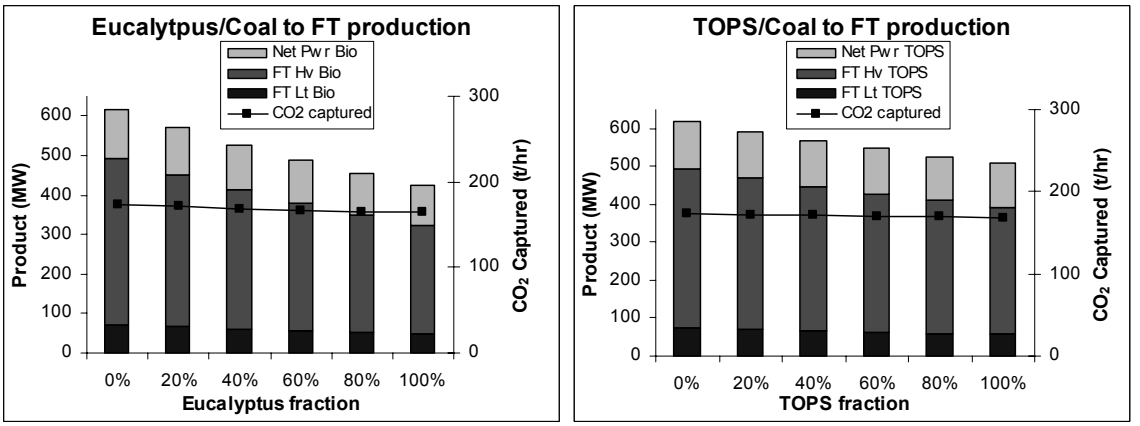

Figure 5 Effect feedstock substitution on FT-fuels production

- Overall efficiencies drop slightly when coal is substituted by biomass. But this drop is small when TOPS is used. The substitution by Eucalyptus does give a moderate drop in efficiency, but also here the maximum drop is when producing methanol and is smaller than 8 percent points. FT-production efficiencies drop from 62% for coal to 60% for TOPS and 57% for Eucalyptus. Methanol and urea production show similar trends. Efficiencies drop for methanol from 55 for to 54 to 52% and for urea from 57 to 56 to 53% for coal, TOPS and Eucalyptus respectively. Power production is the only scenario where efficiencies remain almost constant (40%). Efficiency results of each case are displayed in Figure 6.

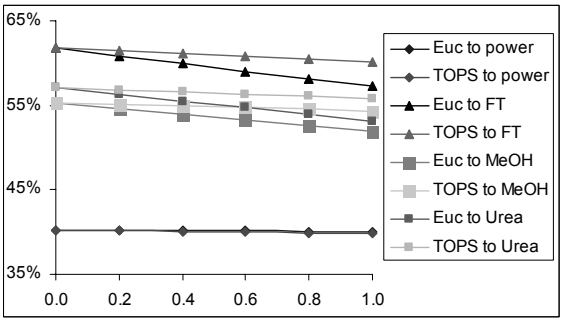

Figure 6 Effect biomass fraction on plant efficiency

4. Discussion and Conclusion

- Feedstock flexibility is technically possible for a Shell EF gasifier. Both raw and torrefied biomass can be used, but torrefaction allows for a higher thermal input and efficiency and thus higher output. Bottlenecks are slag formation and sulphur amount. Biomass has less ash and with a higher melting temperature than coal. This can result in a loss of protective slag layer in the gasifier. Adding flux material and recycling slag, by crushing and adding slag can prevent this. Although this should prevent problems, it does mean constant monitoring of the slag layer. The lower sulphur content can give problems for the Claus and SCOT units as throughputs virtually stops. Recycling sulphur can prevent this.
- Although end product flexibility is technically possible, load variations for the different syngas conversion systems are limited. The large offgas streams of both FT- and methanol production are sufficient energy rich to compensate the small energy poor waste stream leaving the H_2-PSA. For urea the ammonia offgas is unable to compensate the much larger waste stream. There are basically three possible solutions for this. 1) Co-firing natural gas. 2) Lowering the urea production in favour for electricity production. 3) Co-producing FT or methanol as their offgas streams have a high energy density. As long as suitable sized process equipments are used, producing multiple different chemicals is possible
- The CO_2 capture ratio of an IGCF is around 33%. This is only the CO_2 that is extracted by the AGR. When FT-fuels or methanol is produced, CO_2 is also captured in the end product. Therefore, the CO_2 emission ratio is 32% for urea, 20% for methanol and only 6% for FT production. The high CO_2 emission ratio for urea is the result of using the CO_2 captured between the first and second WGS for urea production. The CO_2 produced by the second WGS is vented by the power section. The CO_2 emission ratio can be decreased drastically when the CO_2 rich syngas leaving the second WGS is also directed to the AGR or the AGR is moved downstream of the second WGS.
- Results indicate that flexibility can be achieved with minimal efficiency penalties. When producing chemicals, plant efficiency drops by 2-3 percent point when switching from coal to TOPS and by 6-7 percent points when switching from coal to Eucalyptus. However, CO_2 capture rates are low if urea of electricity is produced. These plants can have much better capture performances when operated non-flexible. Also, the model assumes constant efficiencies for each individual process. For most processes this assumption is valid, but especially the steam cycle can have reduced efficiencies when operated at part-load conditions. Another important consequence of flexibility is that most processes are larger compared to a non-flexible IGCF.

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